

An unusual brightening of Eta Carinae¹

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ABSTRACT

HST/STIS data show that the apparent near-UV, visual-wavelength, and near-IR brightness of η Car increased by a factor of two during 1998. Meanwhile its “Homunculus” ejecta-nebula brightened by about 30%, the largest fluctuation of this type in the past 40 years. These developments were quite unexpected and are not easy to explain. Some dust has probably been destroyed, while the star’s luminosity may have increased even though it was already close to the Eddington Limit. Such a rapid luminosity change would be a truly remarkable phenomenon, not predicted by existing models.

1. INTRODUCTION

Eta Carinae has the most interesting photometric history of any naked-eye star. Conspicuously unstable during the years 1700–1830, it became one of the brightest stars in the sky during its famous giant eruption in 1837–1860, then faded to eighth magnitude, experienced a second eruption around 1890, and faded again (Humphreys et al. 1999). The causes of these great nineteenth-century outbursts are not yet known even after decades of modern research (Davidson & Humphreys 1997). A gradual brightening during the 20th century can be explained by expansion of the dusty “Homunculus” ejecta nebula without necessarily invoking any major change in the star; η Car appears to have been more stable during the past hundred years than it was in the preceding two or three centuries. Aside from the long-term trend, visual-wavelength photometry since 1960 has shown only minor fluctuations of the order of 0.1 magnitude (van Genderen et al. 1994, 1995, 1999).

In this paper we describe a more pronounced brightening that occurred in 1998. It was first publicized after being noticed in HST/STIS data (Davidson et al. 1999), but, somewhat ironically, is almost detectable with the unaided eye. This new phenomenon, more extreme than any brightness change seen in η Car during the past 50 years, may be intrinsic to the star or it may indicate a rapid change in circumstellar extinction, or both; in any case it is a considerable surprise which may have major implications for very massive stars.

Any discussion of Eta’s brightness is complicated by its bright ejecta. In order to avoid severe contamination by nearby ejecta, one must observe the central star with a resolution better than $0.2''$, attained so far mainly with the HST (Davidson et al. 1995). Therefore most ground-based photometry includes the entire Homunculus Nebula as discussed in Section 3 below. In recent years the central star has been an eighth-magnitude object at visual wavelengths while the entire configuration has been a little brighter than $m_V = 6.0$.

In Section 2 we describe the novel HST/STIS results which motivate this paper. Ground-based photometry, discussed in Section 3, confirms that something unusual has happened and constrains

the possible explanations. In Section 4 we explain why those explanations are decidedly non-trivial, while also proposing one or two relevant conjectures about the behavior of this object since its last major eruption a century ago.

2. Brightening seen with HST/STIS

We have observed η Car with the Space Telescope Imaging Spectrograph (STIS) on four occasions listed in Table 1, obtaining slit spectra with the CCD detector. The $0.1''$ -wide slit sampled a variety of emission-line ejecta along with the star, and on two occasions the entire CCD wavelength range (1650–10000Å) was covered with about 30 grating settings; therefore an immense, complex data set has resulted. Since the data reduction is intricate and non-routine, and the continuum brightness was expected to remain fairly steady, we did not examine the absolute flux values until April 1999.

The fluxes listed in Table 1 are based on count rates in a spatial sample of $0.15''$ along the slit, i.e., in a $0.1'' \times 0.15''$ area, where the effective spatial resolution is roughly $0.05''$. Each flux value represents the apparent brightness of the central star, assuming standard STIS sensitivity and correction factors that would be valid for a point source. No corrections for interstellar and circumstellar extinction have been attempted here. We cite wavelengths near 4000 Å and 6800 Å because they were observed on all four occasions, using STIS gratings G430M and G750M. The 4000 Å fluxes are averages of the 3950–3956 Å and 4040–4056 Å continuum, while the 6800 Å values refer to the range 6740–6900 Å; no significant emission lines appear in the star’s spectrum in these intervals. Each 6800 Å flux is an average of two or more separate observation sets. The *absolute* flux calibrations in Table 1 may be uncertain by 10 percent or so, but only *relative* values among the four occasions are essential here. Their likely errors are discussed below.

The obvious trend in flux levels, amounting to factors larger than 2, surprised us and naturally we feared that pointing errors or other instrumental effects might be responsible. Therefore we examined acquisition data for confirmation. For each observing run, initial acquisition of the target object required two short-exposure STIS CCD images, dominated by wavelengths longer

Table 1: HST/STIS observations of η Car, the central star

Date	MJD	Orbits	Slit PA	$F_{\lambda}(4000\text{\AA})^a$	$F_{\lambda}(6800\text{\AA})^a$
1997 Dec 31	50814.0	1	260°	0.83	2.31
1998 Mar 19	50891.6	5	332°	1.00	2.89
1998 Nov 25	51142.2	1	227°	1.68	4.48
1999 Feb 21	51230.6	4	332°	1.99	5.08

^aFlux unit: 10^{-12} erg cm⁻² s⁻¹ Å⁻¹.

than 7000 Å. Then a peakup procedure restricted to wavelengths between 7510 and 8080 Å was used to precisely position the slit. (A second peakup was also done in the middle of the March 1998 observing sequence.) We find that count rates in a 0.25'' square centered at the star increased progressively among the four sets of acquisition images, and so did the peakup rates. Count rates across most of a 4'' region also increased, suggesting that inner parts of the Homunculus nebula brightened as well as the star. Figure 1 shows the various STIS results, which are mutually consistent.

Thus, if this trend is merely an instrumental effect, it must represent a progressive change in derived STIS/CCD detector count rates. A few other stars have also been observed repeatedly with the same instrument and they show no similar trend; for instance, acquisition count rates for the star BD +75° 325 were reasonably steady as shown at the bottom of Fig. 1. In the absence of any plausible instrumental explanation, we conclude that the apparent brightening is real even though it seems astonishingly rapid.

There is no satisfactory way to define the quantitative uncertainties in STIS data like ours. Errors are dominated by practical details such as slit position rather than counting statistics, since many thousands of counts figured in each flux measurement. A proper assessment of the uncertainty would require many independent measurements using separate acquisitions, obviously not feasible in this type of HST project. In March 1998 the 6800 Å flux was observed repeatedly in three different HST orbits, because the same grating tilt also sampled H α emission which required especially careful attention with a range of integration times. Those observations were done both before and after a second peak-up operation. In the resulting data set, the r.m.s. and maximum deviations from the average 6740–6900 Å count rate were 8 and 11 percent. Thus, relative flux measurements like those in Table 1 most likely have r.m.s. errors between 5 and 10 percent, not including the absolute calibration uncertainty. Based on early FOS data with larger uncertainties, in August 1991 the star’s 4000 Å continuum flux was about the same as in early 1998 (Davidson et al. 1995).

The linear fits shown in Fig. 1 have brightening rates of 0.83, 0.73, and 0.57 magnitude per year for wavelengths near 4000, 6800, and 8000 Å. The UV flux around 1800 Å also increased substantially between March 1998 and February 1999, but we omit details because other effects, beyond the scope of this paper, also occurred in the UV. Altogether the STIS data suggest a continuum shift toward shorter wavelengths, contrary to what one expects for a classical LBV-style eruption (see, e.g., Humphreys & Davidson 1994).

The behavior of the emission-line spectrum is far too complex to explore here. Eta’s 1997–1998 “spectroscopic event” was our primary motivation for obtaining STIS data at several different times spanning a 15-month interval. This phenomenon recurs with a 5.5-year period and is not understood (Zanella et al. 1984; Whitelock et al. 1994; Damineli 1996; Damineli et al. 1997; Davidson 1997, 1999). As noted in Section 4 below, however, there is no obvious connection between the brightening reported here and the recent spectroscopic event. The most conspicuous changes related to that event involved emission lines of diffuse ejecta rather than the star; the

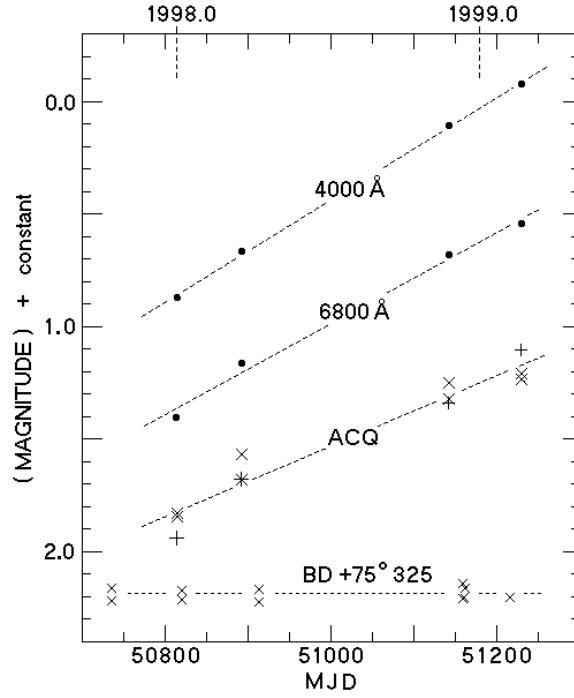


Fig. 1.— HST/STIS flux estimates for η Car, the central star only. Plotted values are like astronomical magnitudes with arbitrary constants added. Data labeled 4000 Å and 6800 Å represent continuum fluxes measured in slit spectra (see text and Table 1). Acquisition count rates are shown as “ACQ”; points marked \times and $+$ are derived respectively from acquisition images and slit-peakup data. Acquisition count rates for another star are shown at the bottom.

qualitative appearance of the star’s bright-line spectrum did not change dramatically. Relatively weak (though physically significant) lines in the stellar wind changed during 1998, and so did the profiles of the bright hydrogen lines, but the total fluxes of the latter increased at roughly the same rate as the underlying continuum. For instance, the equivalent width of $H\alpha$ remained close to 800 Å. In a standard LBV eruption, however, the visual-wavelength continuum brightens faster than the emission lines, which may even become fainter. Beyond these comments, we must postpone the extremely complicated spectroscopic question to later papers.

In summary, the apparent near-UV, visual, and near-IR brightness of *the central star* increased by a factor of 2 or more in fifteen months. Interpolating between wavelengths listed in Table 1, its continuum m_V was close to 8.5 in late 1997 and 7.5 in early 1999. This statement refers to light reaching us directly from the star itself or its wind, not the Homunculus Nebula. (To include emission lines, subtract about 0.1 from the continuum magnitude m_V .)

3. Visual-wavelength photometry of the Homunculus Nebula

Naturally we sought ground-based photometry immediately after noticing the trend in STIS count rates. Results confirm that η Car has become substantially brighter since 1997, but ambiguities in the earlier data make the size of the change uncertain. We suspect that rapid non-monotonic behavior in the mid-1990’s may also play a role in the story.

At normal ground-based spatial resolution η Car itself, the central star, is confused with its ejecta. Photometry therefore usually includes the entire Homunculus nebula, whose major diameter is about 17’’; see many refs. cited in Davidson & Humphreys (1997). The Homunculus is primarily a scattering or reflection, rather than emission, nebula. Its brightness greatly exceeds the light that reaches us directly from the star, and the entire configuration (Homunculus plus star) has been somewhat brighter than $m_V = 6.0$ during the past 15 years. Roughly 20 percent of the star’s visual-wavelength light escapes after being scattered.

Table 2 shows photometric results obtained by four different groups of researchers at three observatories, all during a three-day interval in April 1999. The “CTIO1” BVRI magnitudes

Table 2: Ground-based photometry of the Homunculus,
1999 April 17–19 (MJD 51285–51287)

Instrument (see text)	Aperture size	U	B	V	R _C	I _C
CTIO1	17’’	—	5.84	5.23	4.26	3.81
SAAO	20’’	5.6:	5.96	5.28	4.38	3.92
CTIO2	20’’	5.43	5.90	5.23	—	—
MSO	45’’	—	5.83	5.17	4.20	3.71

were measured by Mario Hamuy with a CCD camera on the 0.9-m telescope at Cerro Tololo Inter-American Observatory. He used a $17''$ aperture for the object, subtracting sky background measured in a $20''$ – $25''$ annulus, with Landolt standard stars (Landolt 1983, 1992). “CTIO2” refers to differential UBV photometry by Travis Metcalfe and Roberta Humphreys with the Texas 3-channel photoelectric photometer (Kleinman et al. 1996) on the Cerro Tololo 1.5-m telescope; sequential observations of η Car and HD 93250 were done with a $20''$ aperture while simultaneously monitoring the sky. The “SAAO” results are photoelectric measurements by Leonid Berdnikov who used the 0.5-m telescope at the South African Astronomical Observatory. Data labeled “MSO” were obtained by Robert Smith and Peter McGregor with the 1.9-m telescope and Monash CCD imager at Mt. Stromlo in Australia, using standard BVRI filters. Measurements in a $45''$ diameter were calibrated relative to the E4-region stars g and h (Graham 1982). Eta’s very bright hydrogen emission lines may cause U, B, R, and I magnitudes to depend appreciably on details of the instrumental response curves, even after standard color-dependent photometric corrections have been applied, because such corrections are based on stars with relatively normal spectra. ‘V’ magnitudes, however, are relatively insensitive to the hydrogen lines. Therefore we omit a discussion of photometric details except for a brief comment on ‘V’, later below.

Considering that strong emission lines and spatial extent make this a difficult object for photometry, the independent results in Table 2 agree with each other remarkably well. They indicate $m_V \approx 5.2$, brighter than η Car has been at any time since about 1864 (Innes 1903, Humphreys et al. 1999). Since van Genderen et al. (1999) gave estimates close to 5.7 for the beginning of 1998, we initially concluded that a 0.5-magnitude brightening had occurred in about a year (Davidson et al. 1999). This seemed consistent with a larger effect in the STIS data, because any change in the reflected light should be delayed and temporally blurred by light-travel times of a few months in the Homunculus.

However, a recent paper by Sterken et al. (1999) indicates a puzzling difficulty for comparisons with the earlier data. The m_V quoted above for early 1998 was said by van Genderen et al. to be a “Johnson V” magnitude derived by transformations from a different photometric system. Using the same system and procedures, Sterken et al. estimate that $m_V \approx 5.5$ a few weeks before our observations reported above — more than 0.2 magnitude fainter than any of our results. Moreover, van Genderen et al. (1995) acknowledged a similar discrepancy in their measures relative to the SAAO instrument in 1992. The data listed in Table 2 were obtained by four different groups of observers using different instruments, different standard stars, and different procedures, with no comparisons of results among the three different observatories while the observations were in progress, and they agree with each other; therefore we will be surprised if they are all 0.2 or 0.3 magnitude too bright. Thus we fear that “Johnson V” magnitudes quoted by van Genderen et al. (1994, 1995, 1999) are systematically too faint.

Reports by experienced non-professional observers are valuable in this connection. W.S.G. Walker has kindly provided us with a data set accumulated over many years by the Auckland (New Zealand) Photoelectric Observers Group. Most of their observations employed one or the other of

two 0.5-m telescopes, using a 30", 40", or 60" photometer aperture with HD 93695 as the primary comparison star. In the 1980's these data were fairly consistent with those of van Genderen's group; the Auckland data tended to be roughly 0.05 magnitude brighter, an insignificant difference as noted below. After 1990, however, the difference increased to at least 0.2 magnitude and the Auckland measures agree well with our results in Table 2 and with the 1992 SAAO observation mentioned above. Several observers² have described recent visual estimates of η Car, in much the same style as those on which its famous nineteenth-century light curve was based. This object is unusually difficult to judge by eye with or without optical aid, because its emission lines may cause differing physiological responses relative to the comparison stars and because it is close to NGC 3372. Their reported magnitudes in April to June 1999 ranged between 4.7 and 5.7, with an average close to 5.3. We also note another recent professional CCD measurement, made after most of this paper had been written: On 1999 June 14, M. Bessell found $m_V = 5.2$ with the 1-m telescope at Mt. Stromlo.

The photometric data related above suggest three conclusions: (1) A standard broadband 'V' magnitude is well defined for η Car and its ejecta, since five independent results in April 1999 all agree to an accuracy better than ± 0.05 magnitude (including an observation by the Auckland group). (2) This magnitude was $m_V \approx 5.2$ in April 1999. (3) The van Genderen et al. (1994, 1995, 1999) "Johnson V" estimates *for times after 1990* are probably more than 0.2 magnitude too faint. The cause of this systematic effect is not obvious. Suppose, for instance, that one obtains data with various response curves that differ from the normal UBV system, and then converts those data to broadband V ("Johnson V") magnitudes with photometric transformations that are valid for normal stars with continuous energy distributions. Then, how large a systematic error may be caused by Eta's notorious emission lines? Informally exploring this question with calculations based on the spectrum found in STIS data, we find that 0.03-to-0.1-magnitude systematic differences are to be expected, a difference of 0.15 magnitude is possible but less likely, and a discrepancy as large as 0.2 magnitude seems excessive. The 'V' band is relatively insensitive to the brightest lines in Eta's spectrum; the largest such contribution, that of $H\alpha$, is probably of the order of 4%. The numerous emission lines of Fe II, etc., are distributed in wavelength, so their overall effect relative to the continuum should not depend critically on the precise 'V' response curve. $H\beta$ emission, however, can perturb "blue" magnitudes which may be used in photometric transformations. Evidently the existing differences need more investigation; they have serious consequences regarding the 1992–1999 behavior of η Car, as noted below.

In any case the ground-based observations indicate a visual-wavelength brightening of about 0.3 magnitude since 1997, not 0.5 as we initially supposed. Eta went from 5.8 magnitude to 5.5 according to van Genderen's group, or from 5.5 to 5.2 according to most other data. Evidently the Homunculus brightened by about 30 percent while HST/STIS count rates on the central star more than doubled; this discrepancy is too large to explain simply by light-travel time in the

²D. Overbeek, P.F. Williams, A. Jones, F. Farrell, J. Garcia, B. Monard.

Homunculus, but other effects noted in Section 4 below can change the apparent star/Homunculus ratio. A 0.3-magnitude brightening of the Homunculus is unusual, as one can see in Fig. 2.

Figure 2 shows the ground-based ‘V’ photometric record over nearly 40 years. Fig. 2a includes data quoted or reported by van Genderen et al. (1994, 1995, 1999) and Sterken (1999) along with our recent measurements listed in Table 2, while the Auckland data appear in Fig. 2b. The long-term trend line in both plots is based on the pre-1992 data in Fig. 2a supplemented by an observation in the early 1950’s. The fluctuating brightness tends to increase by about 0.025 magnitude per year because expansion of the dusty Homunculus allows an increasing fraction of the light to escape (cf. Humphreys et al. 1999, van Genderen et al. 1994, Davidson 1987, and refs. cited there³). For several years after 1991, the van Genderen et al. measures fell very conspicuously below the long-term trend. Alternatively, the other data show a normal-sized but rather brief maximum in 1993, followed by a rapid decline in 1994–1995. Both sets of data agree that substantial brightening occurred after 1995. *In either case the behavior during the 1990’s has been unprecedented in Eta’s modern photometric record which covers the past 40 years:* the low-brightness deviation was extreme in the van Genderen et al. data (Fig. 2a), while in the alternative view that we favor, the brightness has now risen far above the trend line (Table 2 and Fig. 2b). The 1980–1982 brightening episode was comparable but smaller; a careful investigation of data from that time might show whether the central “core” region (star plus close ejecta) brightened much more than the Homunculus did on that occasion.

Sterken et al. (1999) regard the 1997–1999 behavior of η Car as merely a “normal S Doradus phase.” In fact, however, it has been a larger change than any previous event in their data, especially when considered as part of the conspicuous 1992–1999 anomaly in Fig. 2a. The most novel development has arisen in our STIS data, which indicate a much greater apparent brightening of the central star but do not show the cooler spectrum and colors characteristic of an LBV outburst. Altogether, the observations differ appreciably from what one expects for a normal LBV-like photometric fluctuation.

4. Discussion: What is going on?

We have no satisfactory explanation for the rapid brightening described above. The STIS data seem inconsistent with a normal “LBV eruption,” in which bolometric luminosity remains roughly constant but shifts toward longer wavelengths as the photospheric radius expands (see, e.g., Humphreys & Davidson 1994). Since 1997 the flux levels of η Car have increased at nearly all wavelengths in the STIS data, including the bright emission lines of its wind. The two most obvious explanations are that either (1) the bolometric luminosity has increased, or (2) the amount of circumstellar extinction has rapidly decreased. Neither possibility is straightforward, and they

³In a simple model one expects the rate of increase to be appreciably slower than 0.025 magn/yr, but we tentatively assume that the precise rate of the secular trend is not critical for the discussion here.

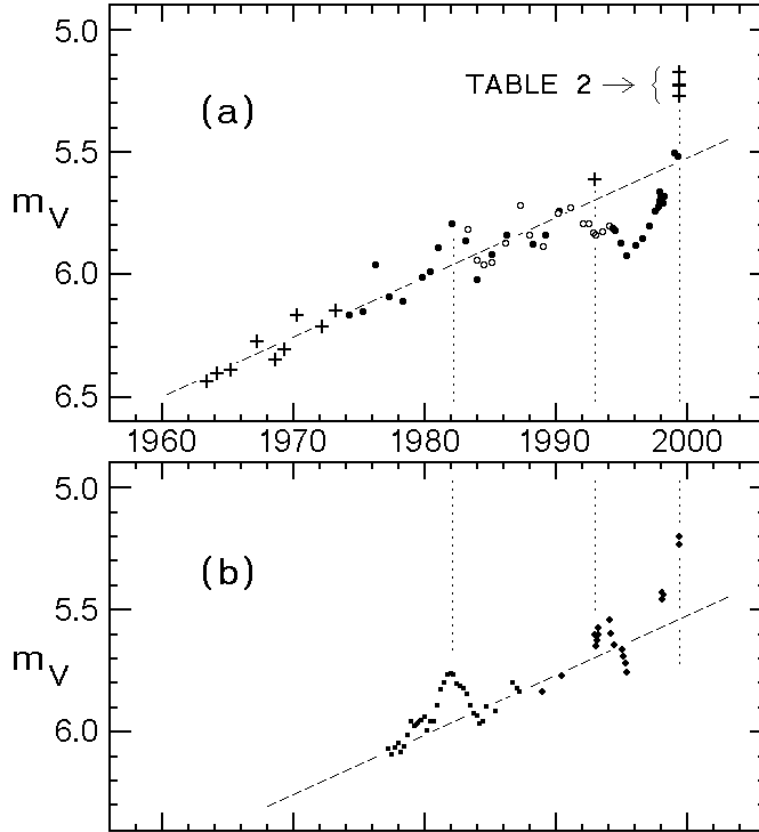


Fig. 2.— Visual-wavelength brightness of the Homunculus since 1960. Most of the pre-1990 points are averages over time intervals of a few months. (a) Data listed by van Genderen et al. (1994, 1995, 1999), Sterken et al. (1999), and in Table 2 of this paper. Crosses represent normal broadband V measurements, filled circles were transformed from other broadband systems, and open circles were derived from narrower-band *uvby* magnitudes. As discussed in the text, perhaps the filled and open circles *after about 1990* should be moved upward in this plot to agree better with the other data. (b) Broadband V magnitudes in the Auckland data set (see text), adjusted to be 0.05 fainter for better consistency with the other measures in the 1980’s. The vertical dotted lines are intended merely to guide the eye between corresponding features in the two plots.

are not mutually exclusive.

Bulk motions of the ejecta do not provide a likely reason for the effective extinction to change abruptly. HST data in the early 1990’s implied that extinction along the line of sight to the central star was much larger than for some of the inner ejecta (Davidson et al. 1995); should we therefore suspect that a compact dense cloud was moving across the line of sight and has now passed it? This explanation for the recent brightening is unappealing for two reasons. First, for reasonable size scales, sufficient motion perpendicular to the line of sight would require far more angular momentum than ejecta should have.⁴ Second, ground-based photometry and STIS acquisition images show that at least the inner parts of the Homunculus have also brightened, not just the star; the phenomenon is not restricted to one line of sight. The required rate of extinction decrease is much faster than the secular effect of nebular expansion (the trend line in Fig. 2).

Therefore, if the extinction has decreased appreciably since 1997, this probably results from destruction, not motion, of circumstellar dust. To some extent this idea is self-consistent: if the optical thickness of the Homunculus is magically reduced by 20%, then the star and Homunculus should indeed brighten by about 0.8 and 0.3 magnitude respectively. Our reasoning is as follows. The central star’s apparent brightness suggests that roughly 4 magn of visual-wavelength circumstellar extinction occurs along the line of sight to it (Davidson et al. 1995), so a 20% reduction in that extinction would cause a ~ 0.8 -magnitude brightening of the central star as reported in Section 2 above. Regarding the brightness of the Homunculus, Fig. 2 of Davidson & Ruiz (1975) provides an idealized but valid summary of the scattering problem. The emergent fraction of visual-wavelength light can be approximated by $\exp(-\alpha\tau)$, where τ is a characteristic optical thickness in the Homunculus and α depends on the albedo of the grains and on geometrical details. The emergent fraction is thought to have been roughly 0.2 a few years ago: $m_V \approx 5.7$ observed for the Homunculus vs. $m_V \approx 4$ expected for the star if it had no circumstellar dust (Davidson & Humphreys 1997). Calculation then shows that a 20% reduction in optical thickness would cause the emergent fraction of light to increase by a factor of roughly 1.38, close enough to the 0.3-magnitude brightening found in Section 3 above. Moreover, if only the innermost grains are destroyed, then they can account for $\sim 20\%$ of the optical thickness even if their total mass is far less than 20% of the dust in the Homunculus. Zanella et al. (1984) suggested that UV radiation may be particularly effective for destroying grains near η Car.

Whitelock et al. (1994) noted that the secular trend of Eta’s near-infrared flux can be attributed to decreasing extinction in the Homunculus only if that extinction has an abnormally weak wavelength dependence, perhaps involving large grains with radii $> 1 \mu\text{m}$. A similar

⁴Suppose the hypothetical dusty cloud has angular momentum corresponding to an orbit at its distance r from the star; for ejecta this is surely an excessive allowance. Then, in order to cross our line of sight in about a year, the size scale of the edge of the cloud must be of the order of $(80 \text{ au}) (r/\text{au})^{-1/2}$. Normal dust grains probably do not exist closer than $r \sim 200 \text{ au}$, so we find a maximum size scale less than 6 au, which would be destroyed by thermal expansion in less than 5 years. More realistic ejecta should have less than a tenth as much angular momentum as we have just assumed, strengthening the case against a moving-occulter explanation for the star’s brightening.

conclusion arises if we explain Fig. 1 in the same way, since the STIS-observed brightening is only modestly wavelength-dependent. The apparent color of the central star also indicates a surprisingly small amount of reddening (Davidson et al. 1995).

There are two serious objections to grain destruction as sole cause of the recent brightening. First, the IR spectrum of the Homunculus shows that most of η Car’s luminosity is absorbed and re-emitted by grains with moderate temperatures of 200–400 K, located thousands of a.u. from the star (see many refs. cited in Davidson & Humphreys 1997). Such grains should be fairly safe from destruction, at least on a time scale less than two years; this is why we used the word “magical” above for a rapid decrease of optical thickness. Hotter, more vulnerable grains closer to the star absorb only a few percent of its light. A second objection is that grain-destruction processes are likely to depend on the star’s energy output — leading us back to the idea of a bolometric luminosity increase even if the circumstellar extinction has changed.

Infrared data are suggestive but tantalizing. Figure 3 shows the relative trends of ‘J’ (1.25 μm), ‘L’ (3.5 μm), and ‘N’ (10 μm) magnitudes for the Homunculus, along with the visual magnitudes discussed in Section 3 above. The IR data are from Whitelock et al. (1994), Gehrz & Smith (1999), Polonski et al. (1999a,b), Russell et al. (1987), Smith et al. (1995), and recent observations by Whitelock et al. The 1.25 μm flux primarily represents free-free emission in the stellar wind, most of the 3.5 μm flux comes from hot dust located a few hundred a.u. ($\sim 0.3''$) from the star, and 10 μm emission is produced by cooler dust, mainly in the inner parts of the Homunculus. Most of our comments on Fig. 3 are fairly obvious but the essential answer to the problem is not.

Figure 3 and the HST data show no definite connection between the recent brightening and the 1997–1998 spectroscopic event. Visual-wavelength and near-IR maxima were correlated with the previous 1981, 1987, and 1992 events; those broad peaks are especially obvious in ‘H’ magnitudes (see Whitelock et al. 1994, the paper where Eta’s 5.5-year cycle was first clearly apparent). Eta’s brightness continued to increase through 1998, long after the spectroscopic event had occurred. A distinct photometric glitch near the end of 1997 coincided with the event (van Genderen et al. 1999, Whitelock & Laney 1999), but lasted only a few weeks and has no clear role in this discussion. If the star and Homunculus become fainter again before the end of 1999, then the recent behavior may resemble the 1980–1982 brightening episode, which may have been related to the 1981 spectroscopic event. Meanwhile there is no reliable evidence to associate the current brightening with the 5.5-year cycle, though we will not be surprised if such a connection exists.

Brightening at $\lambda \sim 1.25 \mu\text{m}$ resembles the visual-wavelength record (Fig. 3). If the 1.25 μm fluctuations are caused simply by varying circumstellar extinction, such extinction must be rather insensitive to wavelength as noted above. Alternatively, perhaps the wind has been evolving on a circa-50-year time scale. In that case, the increased free-free emission suggests that the star has become hotter, not cooler.

Figure 3 shows that the 3.5 μm flux, presumably emitted by the hottest dust, has been

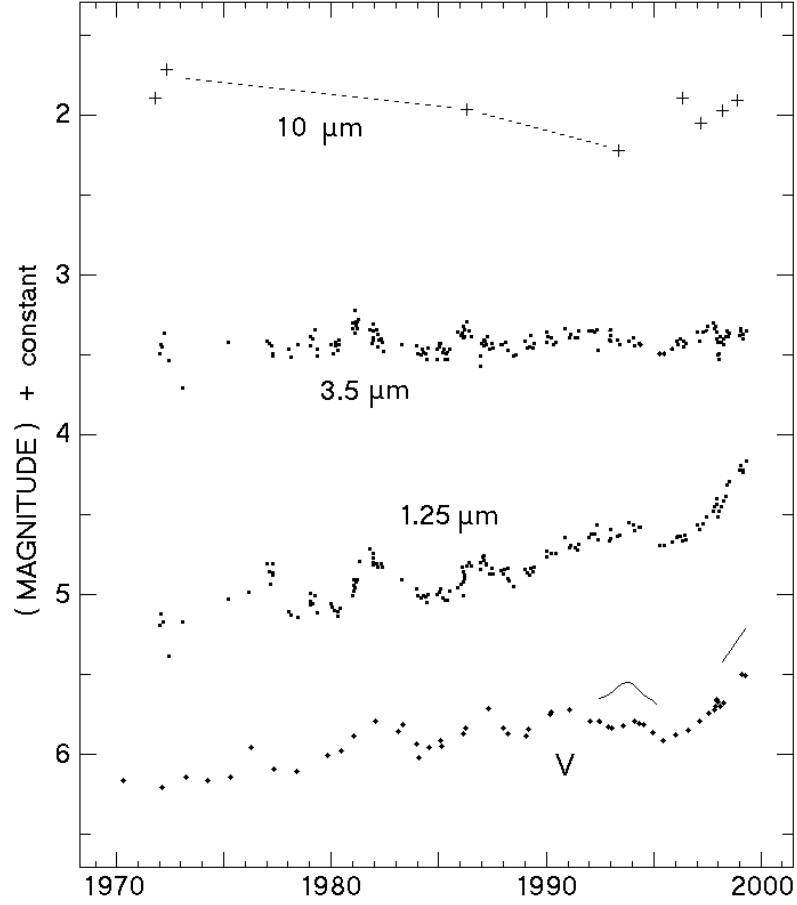


Fig. 3.— The brightness of the Homunculus since 1970 in four wavelength regions from 0.55 to 10 μm , based on data cited in text. A different constant is added to each type of magnitude. Visual-wavelength points near the lower right corner are the van Genderen et al. data in Fig. 2a, while the corresponding thin lines agree with Fig. 2b.

relatively steady. At first sight this looks like evidence against recent variations in the star’s bolometric luminosity. Such an argument is highly questionable, though, since the hottest, most recently formed grains ($T > 500$ K) absorb and re-emit only a small fraction of the luminosity. The amount of light that they intercept is automatically regulated to some extent, because their location and total mass depend on the star’s luminosity and mass-loss rate (cf. remarks in Davidson et al. 1986). For example, suppose that the luminosity increases suddenly. Then the recently-formed innermost grains are destroyed while the grain-formation zone moves slightly outward, where the mass density is slightly smaller. As a result the effective optical depth of the hottest grains is decreased, so they absorb and re-emit a smaller fraction of the luminosity. The stellar wind and the grain-formation rate may also fluctuate; but in any case the quantitative relation between the star’s luminosity and the $3.5\ \mu\text{m}$ brightness is not obvious.

In principle, wavelengths of 10 or $20\ \mu\text{m}$ should indicate luminosity variations better because they represent cooler grains farther from the star. Unfortunately the available data are unsatisfying both in homogeneity and in temporal coverage, as indicated by the $10\ \mu\text{m}$ data at the top of Fig. 3. A gradual decrease from 1970 to 1993 is plausible because one expects most of the dust to become cooler as the Homunculus expands. The more recent $10\ \mu\text{m}$ observations then suggest that the luminosity has increased since 1993, but the uncertainties are too large to permit a robust conclusion. Since the luminosity question is so important for understanding η Car, a series of independent, repeated, unusually careful observations of its fluxes at wavelengths longer than $5\ \mu\text{m}$ during the next few years would be quite valuable.

Eta’s luminosity cannot have increased by a factor of two, because the star is thought to be within $\sim 30\%$ of the Eddington Limit (Davidson & Humphreys 1997). If a super-Eddington luminosity occurs, as probably happened in the nineteenth-century Great Eruption, then the wind should become so dense that its spectrum looks like an F-type supergiant star, contrary to the STIS data.

On the other hand, we can imagine reasons for moderate luminosity variations. After the giant nineteenth-century outbursts the star must have been far from thermal equilibrium, with a characteristic recovery time between 10 and 1000 years, depending on what fraction of the star’s mass is relevant. Suppose that after the eruptions, some interior region had more or less than its normal share of heat; then a consequent change in luminosity would appear much later, when energy from that layer reaches the surface. This is obviously a speculation with no supporting quantitative analysis, but we cite it to suggest that luminosity fluctuations cannot be ruled out.

According to the discussion above, neither an LBV-style eruption, nor a luminosity increase, nor a decrease in circumstellar extinction constitutes a straightforward explanation for the observations reported in Sections 2 and 3. Let us propose a maximum-intuitive-entropy or minimum-absurdity hypothesis. Suppose, first, that much of the star’s obscuration along our line of sight is due to hot grains that are relatively close to the star; i.e., its apparent extinction is not typical of the Homunculus where cooler grains predominate. Then suppose that the luminosity increased in 1997–1999 by some modest amount, say 10 or 15 percent. (Though fractionally small,

this is a rather strong supposition for a star that is already fairly close to the Eddington Limit.) In such a case, the hottest grains may be destroyed and the grain formation zone moves outward. Hypothetical results: The star itself appears dramatically brighter because its line-of-sight extinction has been substantially reduced, while the Homunculus brightens by a lesser amount due to a combination of modestly larger intrinsic brightness and modestly smaller circumstellar extinction. We have no particular confidence that this is the correct explanation, but it seems plausible and illustrates that the observed behavior is not absurd from a theoretical viewpoint.

The hypotheses of a significant luminosity increase and of rapid grain destruction are each, independently, of great theoretical interest; and we cannot yet rule out the possibility of a new major eruption. Evidently η Car, always a rewarding subject for observation, merits special attention in the next few months and years.

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REFERENCES

- Damineli, A., 1996, *ApJ*, 460, L49
- Damineli, A., Conti, P., & Lopes, D.F. 1997, *New Astr.*, 2, 107
- Davidson, K. 1987, in *Instabilities of Luminous Early Type Stars*, ed. H. Lamers & C. de Loore (Dordrecht: Reidel), 127
- Davidson, K. 1997, *New Astr.*, 2, 397
- Davidson, K. 1999, in *Eta Carinae at the Millennium*, ASP Conf. Ser. 300, ed. J.A. Morse, R.M. Humphreys, & A. Damineli, in press.
- Davidson, K., & Ruiz, M.T. 1975, *ApJ*, 202, 421
- Davidson, K., Dufour, R.J., Walborn, N.R., & Gull, T.R. 1986, *ApJ*, 305, 867
- Davidson, K., Ebbets, D., Weigelt, G., Humphreys, R.M., Hajian, A.R., Walborn, N.R., & Rosa, M. 1995, *AJ*, 109, 1784
- Davidson, K., & Humphreys, R.M. 1997, *ARA&A*, 35, 1
- Davidson, K., Humphreys, R.M., Ishibashi, K., Gull, T.R., et al. 1999, *IAU Circ.* 7146
- Gehrz, R.D., & Smith, N. 1999, in *Eta Carinae at the Millennium*, ASP Conf. Ser. 300, ed. J.A. Morse, R.M. Humphreys, & A. Damineli, in press.
- van Genderen, A.M., de Groot, M.J.H., & Thé, P.S. 1994, *A&A*, 283, 89
- van Genderen, A.M., Sterken, C., de Groot, M., Stahl, O., et many al. 1995, *A&A*, 304, 415
- van Genderen, A.M., Sterken, C., de Groot, M., & Burki, G. 1999, *A&A*, 343, 847
- Graham, J.A. 1982, *PASP*, 94, 244
- Humphreys, R.M., & Davidson, K. 1994, *PASP*, 106, 1025
- Humphreys, R.M., Davidson, K., & Smith, N. 1999, *PASP*, in press
- Innes, R.T.A. 1903, *Cape Ann.*, 9, 75B
- Kleinman, S.J., Nather, R.E., & Phillips, T. 1996, *PASP*, 108, 356
- Landolt, A.U. 1983, *AJ*, 88, 439
- Landolt, A.U. 1992, *AJ*, 104, 340
- Polonski, E., Telesco, C., & Piña, R. 1999a, in *Eta Carinae at the Millennium*, ASP Conf. Ser. 300, ed. J.A. Morse, R.M. Humphreys, & A. Damineli, in press
- Polonski, E.F., Telesco, C.M., Piña, R.K., & Fisher, R.S. 1999b, *AJ*, in press
- Russell, R.W., Lynch, D.K., Hackwell, J.A., Rudy, R.J., & Rossano, G.S. 1987, *ApJ*, 321, 937
- Smith, C.H., Aitken, D.K., Moore, T.J.T., Roche, P.F., Puetter, R.C., & Piña, R.K. 1995, *MNRAS*, 273, 354
- Sterken, C., Freyhammer, L., Arentoft, T., & van Genderen, A.M. 1999, *A&A*, 346, L33

- Whitelock, P.A., Feast, M.W., Koen, C., Roberts, G., & Carter, B.S. 1994, MNRAS, 270, 364
- Whitelock, P.A., & Laney, D. 1999, in *Eta Carinae at the Millennium*, ASP Conf. Ser. 300, ed. J.A. Morse, R.M. Humphreys, & A. Damineli, in press
- Zanella, R., Wolf, B., & Stahl, O. 1984, A&A, 137, 79